in its axial spin change in cycles that repeat over tens and hundreds of millennia (DIRS 151945-CRWMS M&O 2000, p. 6.3-4). Correlations have been made between these global position changes and long duration traces, or evidence, of paleoclimate conditions in the region. Two of the primary sources of this evidence are calcite deposited on the walls of rock fractures at Devils Hole in Nevada and lake deposits at the historic Owens Lake location in California. In these examples, analysis of residues left behind has provided insights into climate conditions as far back as 600,000 to 850,000 years ago (DIRS 151945-CRWMS M&O 2000, pp. 6.3-9 and 6.3-12).

Climate regimes believed to have existed in Yucca Mountain's past, and therefore that should occur in its future, have been grouped into the following categories: (1) a warm and dry, modern-like interglacial climate; (2) a warm and wet monsoon climate; (3) an intermediate glacial transition climate; and (4) glacial periods (DIRS 151945-CRWMS M&O 2000, pp. 6.4-11 and 6.4-17). The driest of these climate groupings is the modern-like interglacial climate and (as indicated by its name) represents the climate currently being experienced at Yucca Mountain. Characteristics of these climate regimes and postulated future durations are included as input parameters to the long-term performance assessment modeling performed for the site (DIRS 153246-CRWMS M&O 2000, pp. 3-38 to 3-42).

3.1.3 GEOLOGY

DOE has studied the existing physiographic setting (characteristic landforms), *stratigraphy* (rock strata), and geologic structure (structural features resulting from rock deformations) at Yucca Mountain and in the surrounding region. These studies have yielded detailed information about the surface and subsurface features in the region. This section describes the region of influence for geology, which includes the baseline conditions of the region's geology as well as the specific geology of Yucca Mountain. DOE investigated seismicity (*earthquake* activity) in the Yucca Mountain region; the investigations focused on understanding the Quaternary history of movement on faults in the region and the historic record of earthquake activity. The Department also investigated volcanoes in the Yucca Mountain region to assess the potential for volcanism to result in adverse effects to a repository. In addition, DOE considered the possibility that there might be minerals and energy resources at or near the site of the proposed repository.

3.1.3.1 Physiography (Characteristic Landforms)

Yucca Mountain is in the southern part of the *Great Basin* subprovince of the Basin and Range Physiographic Province (Figure 3-4), a region characterized by generally north-trending, linear mountain ranges separated by intervening valleys (basins) (DIRS 151945-CRWMS M&O 2000, p. 2.2-1). The Great Basin encompasses nearly all of Nevada plus parts of Utah, Idaho, Oregon, and California. Mountain ranges of the Great Basin, including Yucca Mountain, are mostly tilted, fault-bounded crustal blocks that are as much as 80 kilometers (50 miles) long and 8 to 24 kilometers (5 to 15 miles) wide. Ranges typically rise from 300 to 1,500 meters (1,000 to 4,900 feet) above the adjacent valley floors and occupy 40 to 50 percent of the total land area (DIRS 151945-CRWMS M&O 2000, pp. 4.4-1 and 4.4-2).

Valleys between the mountain ranges are filled with alluvial sediments (deposits of sand, mud, and other such materials formed by flowing water) from the adjacent ranges. Many valleys are called *closed basins* because they, like the Great Basin on a regional scale, lack a drainage outlet (DIRS 151945-CRWMS M&O 2000, p. 2.2-1). Water and sediment from adjacent ranges become trapped and move to the lowest part of such valleys to form a *playa*, a flat area that is largely vegetation-free owing to high salinity, which results from evaporation of the water. Valleys with drainage outlets have intermittent stream channels that carry eroded sediment to lower drainage areas.

The present landscape, distinguished by the broad series of elongated mountain ranges alternating with parallel valleys, is the result of past episodes of faulting that elevated the ranges above the adjacent valleys. Section 3.1.3.2 addresses such faulting. Yucca Mountain is an irregularly shaped volcanic

Almost without exception, west-facing slopes at Yucca Mountain are steep and east-facing slopes are gentle, which expresses the underlying geologic structure (see Section 3.1.3.2). Small valleys eroded in the mountain are narrow, V-shaped drainages that flatten and broaden near the mountain base. The crest of Yucca Mountain reaches elevations from 1,500 meters (4,900 feet) to 1,900 meters (6,300 feet) above sea level. The bottoms of the adjacent valleys are approximately 650 meters (2,100 feet) lower (DIRS 151945-CRWMS M&O 2000, p. 4.4-4).

Yucca Mountain is bordered on the north by Pinnacles Ridge and *Beatty Wash*, on the west by *Crater Flat*, on the south by the Amargosa Desert, and on the east by the Calico Hills and by *Jackass Flats*, which contains *Fortymile Wash* (Figure 3-6). Beatty Wash is one of the largest tributaries of the Amargosa River and drains the region north and west of Pinnacles Ridge, including the northern end of Yucca Mountain.

Crater Flat (Figure 3-6) is an oval-shaped valley between Yucca Mountain and *Bare Mountain*. It contains four prominent volcanic cinder cones and related lava flows that rise above the valley floor. Crater Flat drains to the Amargosa River through a gap in the southern end of the basin.

Jackass Flats is an oval-shaped valley east of Yucca Mountain bordered by Yucca, Shoshone, Skull, and Little Skull Mountains (Figure 3-6). It drains southward to the *Amargosa River*. *Fortymile Wash* is the most prominent drainage through Jackass Flats to the Amargosa River.

Site Stratigraphy and Lithology

The exposed stratigraphic section at Yucca Mountain is dominated by mid-Tertiary volcanic ash-flow and ash-fall deposits with minor lava flows and reworked materials. These deposits originated in the calderas shown in Figure 3-5. Regionally, the thick series of volcanic rocks that form Yucca Mountain overlies *Paleozoic* sedimentary rocks that are largely of marine origin. The volcanic rocks, in turn, are covered in many areas by a variety of late Tertiary and Quaternary surficial deposits (DIRS 151945-CRWMS M&O 2000, p. 4.5-1). The stratigraphic section is summarized in Table 3-6, which depicts rock assemblages according to the geologic age during which they were deposited. The stratigraphic sequence of the Yucca Mountain area consists, from oldest to youngest, of Pre-Cenozoic (that is, Paleozoic and Precambrian) sedimentary and metasedimentary (sedimentary rocks that have been altered by metamorphism), mid-Tertiary siliceous (rich in silica) volcanic rocks, Tertiary to Quaternary basalts, and late Tertiary to late Quaternary surficial deposits.

Only Tertiary and younger rocks are exposed at Yucca Mountain (DIRS 151945-CRWMS M&O 2000, p. 4.5-1). Parts of the older (Pre-Cenozoic) rock assemblages described in Table 3-6 are exposed at Bare Mountain, the Calico Hills, and the Striped Hills, to the east, northeast, and southeast of Yucca Mountain, respectively (see Figure 3-6) (DIRS 151945-CRWMS M&O 2000, Figures 4.2-3 to 4.2-6, pp. F4.2-3 to F4.2-6). Many of these older rocks are widespread in the Great Basin where their cumulative thickness is thousands of feet. Detailed information about their characteristics is lacking at Yucca Mountain because only one *borehole*, about 2 kilometers (1.2 miles) east of Yucca Mountain, has penetrated these rocks. Paleozoic carbonate rocks were penetrated in this borehole at a depth of about 1,250 meters (4,100 feet) (DIRS 102046-Carr et al. 1986, p. 5-5). Paleozoic carbonate rocks form important aquifers in southern Nevada (DIRS 101167-Winograd and Thordarson 1975, all).

Table 3-7 lists the principal mid-Tertiary volcanic stratigraphic units mapped at the surface, encountered in boreholes, and examined in the Exploratory Studies Facility that have been a major focus of site characterization investigations. The proposed repository and access to it would be entirely in the Paintbrush Group, so investigations have focused particularly on the formations in that stratigraphic unit. Detailed descriptions of the volcanic stratigraphic units are in the Yucca Mountain Project Stratigraphic Compendium (DIRS 101535-CRWMS M&O 1996, all). The following paragraphs provide a general

Table 3-6. Highly generalized stratigraphy summary for the Yucca Mountain region.[a]

Geologic age designation	Major rock types (lithologies)
Cenozoic Era	
Quaternary Period (< 1.6 Ma)[b]	Alluvium; basalt
Tertiary Period (< 65 - 1.6 Ma)	Silicic ash-flow tuffs; minor basalts. Predominantly volcanic rocks of the southwestern Nevada volcanic field (includes Topopah Spring Tuff, host rock for the potential repository). Table 3-7 lists major Tertiary volcanic formations at Yucca Mountain.
Mesozoic Era (240 - 65 Ma)	No rocks of this age found in Yucca Mountain region.
Paleozoic Era (570 - 240 Ma)	Three major lithologic groups (lithosomes) predominate: a lower (older) carbonate (limestone, dolomite) lithosome deposited during the Cambrian through Devonian Periods (see Figure 3-17), a middle fine-grained clastic lithosome (shale, sandstone) formed during the Mississippian Period, and an upper (younger) carbonate lithosome formed during the Pennsylvanian and Permian Periods.
Precambrian Era (> 570 Ma)	Quartzite, conglomerates, shale, limestone, and dolomite that overlie older igneous and metamorphic rocks that form the crystalline "basement."

a. Source: Adapted from DIRS 151945-CRWMS M&O (2000, pp. 4.2-3 to 4.2-20).
b. Ma = approximate years ago in millions.

summary based on the *Yucca Mountain Site Description* (DIRS 151945-CRWMS M&O 2000, pp. 4.5-1 to 4.5-34).

The bulk of the volcanic sequence consists of tuffs. Volcanic rocks known as ash-flow tuffs (or *pyroclastic* flow deposits) form when a hot mixture of volcanic gas and ash violently erupts and flows.

As the ash settles, it is subjected to various degrees of compaction and fusion depending on temperature and pressure conditions. If the temperature is high enough, glass and pumice fragments are compressed and fused to produce welded tuff (a hard, brick-like rock with very little open pore space in the rock *matrix*). Nonwelded tuffs, compacted and consolidated at lower temperatures, are less dense and brittle and generally have greater porosity. Ash-fall tuffs are formed from ash that cooled before settling on the ground surface, and bedded tuffs are composed of ash that has been reworked by stream action. All of these are found in the volcanic assemblage at Yucca Mountain.

In general, characterization of the various volcanic units is based on changes in depositional features, the development of zones of welding and devitrification (crystallization of glassy material), and the development of alteration products in some rocks. Mineral and chemical composition and properties such as density and porosity also have been used in distinguishing some units. Most of the formations listed in Table 3-7 contain phenocrysts (mineral grains distinctly larger than the surrounding rock matrix) and lithic clasts (rock fragments), have some part that is at least partially welded, and typically have some part that has devitrified during cooling of the deposit. In addition, the vitric (glassy) parts of many formations have been partly altered to clay and *zeolite* minerals, and all the rocks have developed various amounts of fractures, some of which contain secondary mineral fillings.

Lithophysal cavities are prominent features in some units, notably in the Tiva Canyon and Topopah Spring Tuffs, where they range from 1 to 50 centimeters (0.4 to 20 inches) in diameter and are a basis for the further subdivision of these formations. Lithophysal cavities are voids resulting from vapors trapped in densely welded parts of the formations. Lithophysal zones contain fewer fractures compared to nonlithophysal zones.

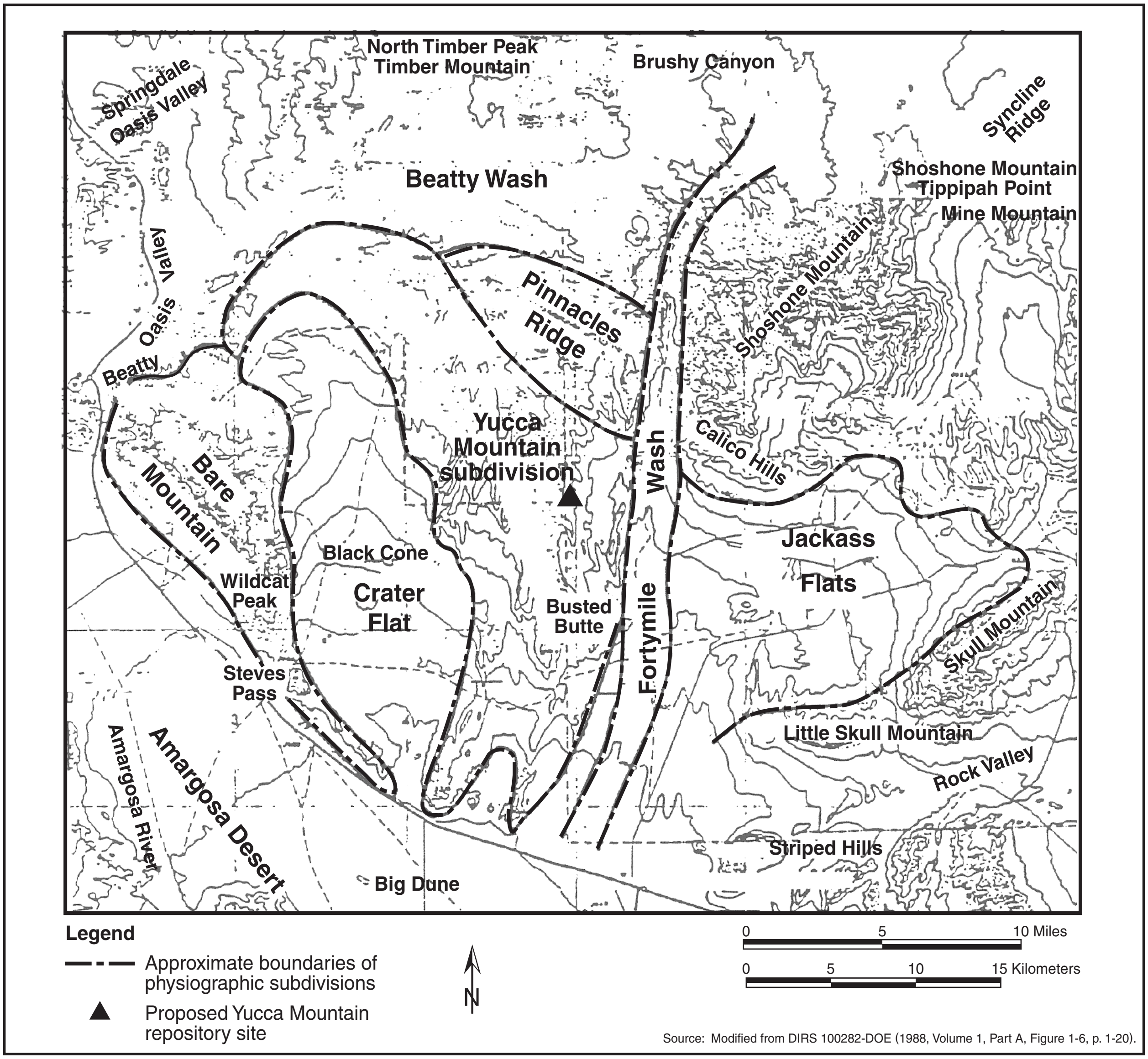

Figure 3-6. Physiographic subdivisions in the Yucca Mountain vicinity.

Although welded tuffs dominate the volcanic sequence, bedded tuffs are present in the Paintbrush Group and in some older parts of the sequence (DIRS 151945-CRWMS M&O 2000, Figures 4.5-3 and 4.5-4, pp. F4.5-3 to F4.5-4). Joints and fractures are common in the welded tuffs, producing much greater bulk permeabilities than those of the nonwelded and bedded tuffs (DIRS 151945-CRWMS M&O 2000, p. 4.10-6). This is an important distinction with regard to investigation of hydrologic conditions.

Some parts of the volcanic formations contain secondary mineral products created by alteration of the original materials after their original deposition and consolidation. Some alteration has resulted from reactions with groundwater, and the types of new mineral substances found can differ based on occurrence below or above the water table. Alteration products such as clay minerals and zeolites occur in several parts of the volcanic sequence; in some places, in-filling with zeolites has reduced the porosity and thus affected hydrologic properties. In most of the formations, contacts between vitric and devitrified layers are commonly marked by an interval containing clay or zeolite alteration minerals. A notable example is the interval, as much as several meters thick, where glassy rock at the base of the Topopah

Table 3-7. Tertiary volcanic rock sequence at Yucca Mountain.[a]

Name	Age (millions of years)[b]	Thickness (meters)[c]	Characteristics
Timber Mountain Group			
• Ammonia Tanks Tuff	11.5	Up to 215	Welded to nonwelded rhyolite tuff; exposed in southern Crater Flat.
• Rainier Mesa Tuff	11.6	< 30 - 240	Nonwelded to moderately welded vitric to devitrified tuff exposed locally along downthrown sides of large normal faults.
Post-Tiva Canyon, pre-Rainier Mesa Tuffs	12.5	0 - 61	Pyroclastic flows and fallout tephra deposits in subsurface along east flank of Yucca Mountain.
Paintbrush Group			Four formations (below) interlayered locally with lava flows and reworked volcanic deposits.
• Tiva Canyon Tuff	12.7	< 50 - 175	Crystal-rich to crystal-poor densely welded rhyolite tuff that forms most rock at surface of Yucca Mountain.
• Yucca Mountain Tuff	--[d]	0 - 45	Mostly nonwelded tuff but is partially to densely welded where it thickens to north and west.
• Pah Canyon Tuff	--	0 - 70	Northward-thickening nonwelded to moderately welded tuff with pumice fragments.
• Topopah Spring Tuff	12.8	Up to 380	Rhyolite tuff divided into upper crystal-rich member and lower crystal-poor member. Each member contains variations in lithophysal content, zones of crystallization, and fracture density. Glassy unit (vitrophyre) present at the base. Proposed host for repository.
Calico Hills Formation	12.9	15 - 460	Northward-thickening series of pyroclastic flows, fallout deposits, lavas, and basal sandstone; abundant zeolites except where entire formation is vitric in southwest part of central block of Yucca Mountain.
Crater Flat Group			Pyroclastic flows and interbedded tuffs of rhyolitic composition distinguished by abundance of quartz and biotite.
• Prow Pass Tuff	13.1	60 - 228	Sequence of variably welded pyroclastic deposits.
• Bullfrog Tuff	13.3	76 - 275	Partially welded, zeolitic upper and lower parts separated by a central densely welded tuff.
• Tram Tuff	13.5	60 - 396	Lower lithic-rich unit overlain by upper lithic-poor unit.
Lithic Ridge Tuff	13.9	185 - 304	Southward thickening wedge of welded and nonwelded pyroclastic flows and interbedded tuff extensively altered to clays and zeolites.
Pre-Lithic Ridge	+14.0	45 - 350	Mostly altered pyroclastic flows, lavas, and bedded tuff of rhyolitic composition.

a. Modified from DIRS 151945-CRWMS M&O (2000, pp. 4.5-19 to 4.5-33).
b. Source: DIRS 151945-CRWMS M&O (2000, Table 4.2-3, p. T4.2-3).
c. To convert meters to feet, multiply by 3.208.
d. -- = no absolute dates.

the further subdivision of these formations. Lithophysal cavities are voids resulting from vapors trapped in densely welded parts of the formations. Lithophysal zones contain fewer fractures compared to nonlithophysal zones.

Spring Tuff (the basal *vitrophyre*) is in contact with the overlying nonlithophysal zone; this interval of alteration occurs in most boreholes in the vicinity of the proposed site (DIRS 151945-CRWMS M&O 2000, p. 4.5-11). Subtle differences in geochemical conditions are believed to have given rise locally over short distances to some unusual zeolites. One in particular is the fibrous zeolite *erionite*, which is a potential human health hazard (see Section 3.1.8.3). Data from rock samples show that in the potential repository horizon erionite, if it occurs, is either in the altered zone immediately above the Topopah Spring lower vitrophyre or in the moderately welded zone underlying this vitrophyre. It has also been identified in the lower Tiva Canyon Tuff (DIRS 101779-DOE 1998, Volume 1, p. 2-25).

Figure 3-7 is a geologic map that shows the surficial distribution of Tertiary volcanic units and younger surficial deposits in the vicinity of the proposed site. Figure 3-8 is a vertical cross-section through the southern part of this area that shows the subsurface expression of the mapped units, including structural aspects (east-dipping rock units and predominantly west-dipping normal faults). Examples of Tertiary units include the lava flows that cap Skull and Little Skull Mountains at the south and southeast margins of Jackass Flats, a *basalt* ridge that forms the southern boundary of Crater Flat, and a basaltic dike dated at 10 million years (DIRS 151945-CRWMS M&O 2000, p. 4.5-33) that intrudes in the northern part of the Solitario Canyon fault, which bounds the west flank of Yucca Mountain. Volcanic rocks younger than the Tertiary units occur locally at and in the Yucca Mountain vicinity but are of limited extent (Figure 3-5). They represent low-volume eruptions typically consisting of a single main cone surrounded by a small field of basalt flows. A north-trending series of cinder cones and lava flows on the southeast side of Crater Flat has been dated at 3.7 million years, and in the center of Crater Flat a series of four northeast-trending cinder cones (Qbo in Figure 3-5) has been dated at about 1 million years. The youngest basaltic center is the Lathrop Wells center, which is a single cone estimated to be 80,000 years old, with several different age dating methods putting the age between 70,000 and 90,000 years (DIRS 151945-CRWMS M&O 2000, p. 12.2-5). Some authors, however, cite evidence for *polycyclic volcanism*, suggesting a significant time interval between the emplacement of the Lathrop Wells *scoria* deposits.

The youngest stratigraphic units at Yucca Mountain are the predominantly unconsolidated surficial deposits of late Tertiary and Quaternary age. They are shown in Figure 3-7 as *alluvium* (material such as sand, silt, clay, pebbles, cobbles, or even boulders deposited on land by water) and *colluvium* (loose earth material that has accumulated at the base of a hill through the action of gravity) but have been classified in more detail as stream (alluvial) deposits, hillslope (colluvial) deposits, spring deposits, and windblown (eolian) deposits (DIRS 151945-CRWMS M&O 2000, pp. 4.4-10 to 4.4-21). Most Quaternary units exposed at the surface were deposited during the last 100,000 years (DIRS 101779-DOE 1998, Volume 1, p. 2-26). The bulk of these consist of alluvium deposited by intermittent streams that transported rock debris from hillslopes to adjacent washes and valleys.

Selection of Repository Host Rock

Selection of the potential repository emplacement area was based on several considerations, which include (1) depth below the ground surface sufficient to protect *nuclear waste* from exposure to the environment, (2) extent and characteristics of the host rock, (3) location away from major faults that could adversely affect the stability of underground openings or act as pathways for water flow that could eventually lead to radionuclide release, and (4) location of the water table in relation to the proposed repository (DIRS 104956-CRWMS M&O 1993, pp. 5-99 to 5-101).

DOE selected the middle to lower portion of the Topopah Spring Tuff as the potential repository horizon. The rock is strongly welded with variable *fracture* density and void space; experience gained from the excavation of the Exploratory Studies Facility shows the capability to construct stable openings in this rock. Thermal and mechanical properties of this section of rock should enable it to accommodate the range of temperatures anticipated (thermal properties will not be affected greatly by construction and operation, as compared to postemplacement), and the identified repository volume is between major faults. Finally, the selected repository horizon is well above the present groundwater table. Based on geologic evidence the water table under Yucca Mountain has not been more than about 120 meters (390 feet) higher than its present level in the past several hundred thousand years; at such levels the water table would still be about 40 to 280 meters (130 to 920 feet) below the selected repository horizon (DIRS 151945-CRWMS M&O 2000, p. 9.4-1). Section 3.1.4 discusses the water table level further.

Potential for Volcanism at the Yucca Mountain Site

DOE has performed extensive investigations to determine the ages and nature of the volcanic episodes that produced the rocks described above (DIRS 151945-CRWMS M&O 2000, Chapters 4, 5, and 12). The rocks that form the southwestern Nevada volcanic field, characterized by large-volume silicic ash flows (including the host rock for the proposed repository), were erupted during a period of intense tectonic activity associated with active geologic faulting (DIRS 100075-Sawyer et al. 1994, all). The volcanism that produced these ash flows is complete (has not occurred in the region for more than 7.5 million years) and, based on the geology of similar volcanic systems in the Great Basin, no additional large-volume silicic activity is likely (DIRS 101779-DOE 1998, Volume 1, p. 2-85).

Basaltic volcanism in the Yucca Mountain region began about 11 million years ago as silicic eruptions waned and continued as recently as about 80,000 years ago. Basaltic volcanic events were much smaller in magnitude and less explosive than the events that produced the ash flows mentioned above. Typical products are the small volcanoes or cinder cones and associated lava flows in Crater Flat (about 1 million years old) and the Lathrop Wells volcano (possibly as young as 80,000 years) (DIRS 151945-CRWMS M&O 2000, p. 4.2-19). The potential for future volcanic activity in the Yucca Mountain region would be associated with basaltic volcanism rather than silicic activity.

Differing views on the likelihood of volcanism near Yucca Mountain result from uncertainties in the hazard assessment. To address these uncertainties, DOE has performed analyses, conducted extensive volcanic hazard assessments, considered alternative interpretations of the geologic data, and consulted with recognized experts, representing other Federal agencies (for example, the U.S. Geological Survey), national laboratories, and universities (for example, the University of Nevada and Stanford University). In 1995 and 1996, a panel of 10 scientists from these agencies and institutions and with expertise in volcanism reviewed the extensive information on volcanic activity in the Yucca Mountain vicinity and assessed the likelihood that future volcanic activity could occur at or in the vicinity of the repository (DIRS 151945-CRWMS M&O 2000, p. 12.2-21).

The probability of basaltic lava intruding into the repository is expressed as the annual probability that a volcanic event would disrupt (intersect) a repository, given that a volcanic event would occur during the period of concern. The expert panel assessed uncertainties associated with the data and models used to evaluate the potential for disruption of the potential Yucca Mountain Repository by a volcanic intrusion (dike) (DIRS 100116-CRWMS M&O 1996, all). The panel estimated the probability of a dike disrupting the repository during the first 10,000 years after closure to be 1 chance in 7,000. The estimate was recalculated to account for the current footprint of the proposed repository. The revised estimate increases to about 1 chance in 6,300 (with 5th and 95th percentiles of 1 chance in 130,000 and 1 chance in 2000, respectively, of a volcanic dike disrupting the repository) during the first 10,000 years with the current repository layout, considering both primary and contingency blocks (DIRS 151945-CRWMS M&O 2000, pp. 12.2-27 and 12.2-28 and Table 12.2-8).